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# EXPERIMENTAL STUDY OF $\sin 2\beta$ AND $\sin 2\alpha$

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Detailed measurements of CP violation in $B$ meson decay are on the horizon. Here I review the status of current measurements of $\sin 2\beta$ made at LEP and CDF. These yield an average of $\sin 2\beta = 0.82 \pm 0.39$, giving 97% confidence that $\beta$ is greater than 0, evidence that CP violation occurs in $B$ decay. I review predictions for the precision we can expect on $\sin 2\beta$ and $\sin 2\alpha$ in the next few years.

## 1 Introduction

Quark weak decay is governed by the unitary CKM matrix. One useful parametrisation of this $3 \times 3$ matrix, due to Wolfenstein, is:

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where $\lambda$ is the Cabbibo mixing angle in strange quark decay while $A, \rho$ and $\eta$ are three other real parameters. The unitarity of this matrix leads to one particularly interesting relationship among the elements:

$$V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0. \quad (1)$$

This can be visualised as a triangle in the $(\rho, \eta)$-plane (see Fig. 1). Constraints on the CKM matrix elements from $B^0\bar{B}^0$ mixing, limits on $B_s^0\bar{B}_s^0$ mixing, $\epsilon_K$ from $K$ meson decay, $V_{ub}$ and $V_{cb}$ lead to a prediction that $\beta = 0.75 \pm 0.09$ [1]. One of the most compelling reasons to measure $\beta$ directly is to verify whether the CKM matrix explains CP violation in the $B$ system.

One form of CP violation in the $B$ system manifests itself in the decay of $B^0$ and $\bar{B}^0$ mesons into a common final state. The angle $\beta$ can be measured from $B^0 \to J/\psi K_S^0$ decays. CP violating effects arise from the interference of direct decays to $J/\psi K_S^0$ with decays that proceed via mixing ($B^0 \to \bar{B}^0$) followed by the same decay. The measured asymmetry, $A_{CP}(t)$, can be related to the CP violating angle $\beta$ by:

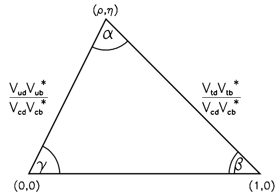


Figure 1. The unitarity triangle showing the angles $\alpha$, $\beta$ and $\gamma$ that will be pursued in the next generation of searches for CP violation in the $B$ sector.

$$\begin{aligned} A_{CP}(t) &= \frac{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_S^0) - \frac{dN}{dt}(B^0 \to J/\psi K_S^0)}{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_S^0) + \frac{dN}{dt}(B^0 \to J/\psi K_S^0)} \\ &= \sin 2\beta \ \sin \Delta m_d t. \end{aligned} \tag{2}$$

There are a number of experimental complications to this clean theoretical situation. At $B$ factories the $B$ mesons are produced from $\Upsilon(4S)$ decay in a, J=1, coherent state. A CP asymmetry can only be observed as a function of the decay length difference between the two $B$ mesons and the time averaged asymmetry vanishes. At hadron colliders $B$ mesons are produced incoherently. Thus we can measure the asymmetry as a function of the single $B$ meson decay length and the time averaged asymmetry does not vanish.

In both cases we must tag the flavour of the decaying $B$ meson Attempts to tag the $B$ meson are limited by the tag efficiency, $\epsilon$, and its dilution, $\mathcal{D}$, which is a measure of the fraction, $f_w$, of incorrectly tagged mesons. The true CP asymmetry is reduced by the dilution:

$$A_{CP}^{obs} = \mathcal{D} A_{CP} \tag{3}$$

where $\mathcal{D}$ is defined as: $\mathcal{D} = (N_r - N_w)/(N_r + N_w) = 1 - 2f_w$, with $N_r(N_w)$ the number of right (wrong) tags. We expect a precision on sin $2\beta$ of:

$$\delta \sin\ 2\beta \propto \frac{1}{\sqrt{\epsilon \mathcal{D}^2}} \sqrt{\frac{S+B}{S^2}} \tag{4}$$

where $S$ is the number of signal candidates and $B$ the number of background candidates in the sample. The product $\epsilon\mathcal{D}^2$ acts as an effective tagging efficiency accounting for the number of fully tagged events. In hadron collider experiments this number can be expected to range from a few % up to 10% while at $B$ factories it ranges from $30 - 40\%$.

## 2 Measurements of $\sin 2\beta$

Several groups have isolated $B \to J/\psi K_S^0$ samples and made measurements of the CP angle $\beta$ [2,3,4]. Here I describe the most precise single measurement [5].

Table 1. Summary of CDF $B$ meson flavour tagging efficiencies and dilutions.

| Tagger | Events | efficiency ($\epsilon$) | Dilution ($\mathcal{D}$) |
|---|---|---|---|
| SST | SVX | $35.5 \pm 3.7$ % | $16.6 \pm 2.2$ % |
| SST | non-SVX | $38.1 \pm 3.9$ % | $17.4 \pm 3.6$ % |
| SLT | all | $5.6 \pm 1.8$ % | $62.5 \pm 14.6$ % |
| JETQ | all | $40.2 \pm 3.9$ % | $23.5 \pm 6.9$ % |

### *2.1 The CDF Result*

From its Run I sample the CDF collaboration has selected a dataset of 400 $J/\psi K_S^0$ $B$ meson decays. About half of these (see Fig. 2a)) have precise lifetime information allowing the extraction of $\sin 2\beta$ from an analysis of the time-dependent asymmetry (see eqn. 2). The other half (see Fig. 2b)) lack silicon information on one or more of the final state tracks. For these events we measure the time averaged asymmetry and extract $\beta$, with less precision, based on the convolution of eqn. 2 with our acceptance for $B$ meson decay.

To extract evidence for a CP violating asymmetry we must determine the initial flavour of the $B$ meson. The final state, a CP eigenstate, provides no clue as to whether a $B^0$ or $\bar{B}^0$ was responsible for the decay. We employ three methods to tag the decaying $B$ meson's flavour. The first involves identifying a fragmentation pion near the $J/\psi K_S^0$ that results from the primary fragmentation. Its charge is related to the flavour of the $B$ meson. We constrain the dilution of this tag with control samples of $B^{\pm}$ mesons and find that same side tagging (SST) yields a dilution of 17% (see table 1). We observe very small differences in the efficiency and dilution of SST for the data samples with/without SVX lifetime information. The other two tagging techniques involve finding another $B$ meson in the event where a $J/\psi K_S^0$ has been reconstructed. This other $B$ meson starts with the opposite flavour of the one that decayed into $J/\psi K_S^0$. However, either of them can mix between their production and decay. This limits the usefulness of the "opposite-side" $B$ meson in flavour tagging. Once found we tag the away side $B$ meson flavour in two ways. If it decays semi-leptonically then the decay lepton charge tags the flavour. This soft lepton tag (SLT) has very high dilution, exceeding 60 % (mixing limits it to a maximum of 74%) but the $B$ meson semileptonic branching fraction (we tag both electrons and muons) results in a small efficiency. We also measure the charge of jets (JETQ) opposite the $B$ that has decayed to $J/\psi K_S^0$. We sum the charge of tracks in a jet, weighting them by momentum and impact parameter, to obtain a measure of their parent parton charge. We do this with relatively high efficiency and find that the optimal

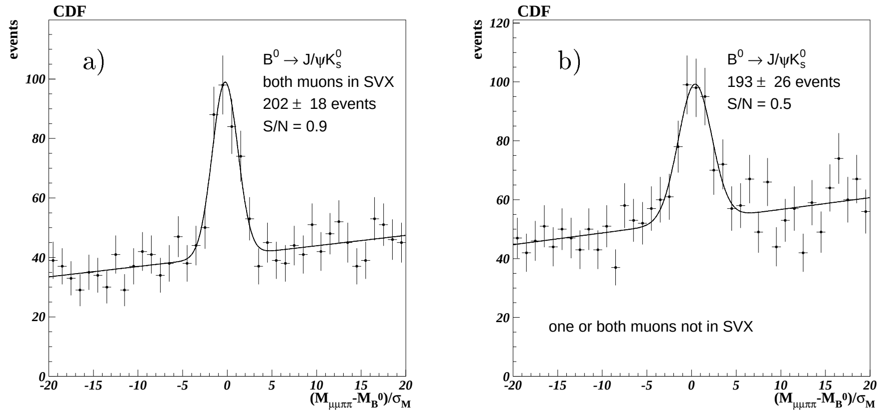


Figure 2. The CDF $J/\psi K^0_S$ data where a) both $J/\psi$ muons have SVX information and b) where one or both $J/\psi$ muons lack SVX information.

algorithm achieves a dilution of 23%.

These tagging algorithms are applied to each decay candidate. If more than one tag is present we compute an effective dilution. If the tags agree the dilution is increased to reflect our increased confidence in the determination of the $B$ flavour. When the tags disagree we reduce the effective dilution. Such candidates end up carrying much less weight in the final fit. Although the dilutions are computed candidate-by-candidate and included in our final fit for $\sin 2\beta$ we predict the expected statistical power of our tagging techniques. Each of the three taggers has an $\epsilon\mathcal{D}^2$ of about 2% and combining them, including correlations, we expect to have an overall $\epsilon\mathcal{D}^2$ of $(6.3 \pm 1.7)\%$. With this tagging efficiency and dilution, our 400 $J/\psi K^0_S$ candidates have the statistical power of 25 perfectly tagged events.

In performing a maximum likelihood fit, we weight each candidate not only by its predicted dilution, but also its observed decay length and mass. Our fit is shown in Fig. 3a). Events with precise lifetime information are plotted, as a function of $ct$, on the left. Our preferred fit is shown as a solid line. The dotted line is the result of a fit with $\Delta m_d$ determined from this data. The value of $\Delta m_d$ changes by one standard deviation but $\sin 2\beta$ extracted from the amplitude of these curves is unchanged. The time-averaged asymmetry of the candidates without precise $ct$ information is shown on the right of Fig. 3a). From the combination of samples we extract $\sin 2\beta = 0.79^{+0.41}_{-0.44}$. Since we include variations of the fit inputs ($\epsilon$, $\mathcal{D}$, $\Delta m_d$, $\tau_B$, etc.) the quoted uncer-

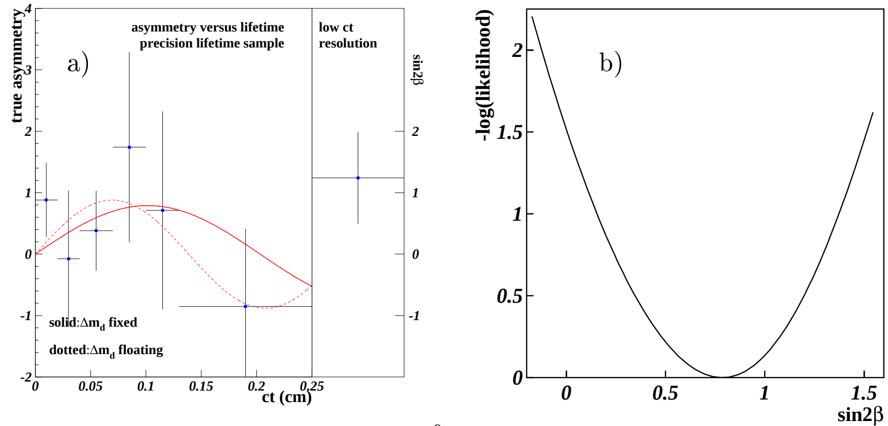


Figure 3. a) Asymmetry observed in $J/\psi K^0_S$ decays. On the left the events with precise vertex information are plotted as a function of decay time. On the right the time averaged asymmetry for events without vertex information is shown. b) A scan of the likelihood scan showing that $\sin 2\beta = 0$ is excluded with 95% CL.

tainties include both statistical and systematic effects. Our only significant systematic is due to uncertainty on the tagging dilutions.

Figure 3b) shows a scan of our likelihood for $\sin 2\beta$. Several techniques for normalising the probability near the physical bound ($\sin 2\beta$ cannot exceed 1) have been tried. The probability that $\sin 2\beta$ is actually 0, given our measurement, is excluded with 93% to 96.4% depending on the method chosen [5].

## *2.2 Other Results*

The OPAL collaboration published a first measurement of the angle $\beta$ from a sample of 24 $J/\psi K^0_S$ candidates including background [2]. CDF also published an initial determination using only the SST tagging algorithm, applied to $J/\psi K^0_S$ candidates with precise lifetime information [3]. This has now been superseded by the measurement described above [5]. Finally, the ALEPH collaboration has presented a preliminary measurement of $\beta$ from 23 $J/\psi K^0_S$ candidates in their data. These results are summarised in table 2.

I have tried combining these results in several ways to produce a "world average" prior to the first measurements from the $e^+e^-$ B factory experiments. In the average quoted I remove the OPAL result as it is far from the physical region. Including it yields a result of $0.91 \pm 0.39$ which artificially inflates the significance by moving the average, without improving the uncertainty. The result I quote, $0.82 \pm 0.39$, excludes $\beta \leq 0$ with 97.5% confidence.

Table 2. Summary of measurements of $\sin 2\beta$ and Standard Model prediction.

| Experiment | $\sin 2\beta$ | Reference |
|---|---|---|
| OPAL | $3.2^{+1.8}_{-2.0}(stat) \pm 0.5(sys)$ | 2 |
| CDF (initial) | $1.8 \pm 1.1(stat) \pm 0.3(sys)$ | 3 |
| CDF (update) | $0.79 \pm 0.39(stat) \pm 0.16(sys)$ | 5 |
| ALEPH (prelim) | $0.93^{+0.64}_{-0.88}(stat)^{+0.36}_{-0.24}(sys)$ | 4 |
| My Average | $0.82 \pm 0.39$ | |
| CKM model fit | $0.75 \pm 0.09$ | 1 |

## 3 The Future of CP Violation Measurements in $B$ Decay

The measurements made so far only hint at CP violation in $B$ meson decay. Dedicated $B$ factory experiments were beginning to take data as this meeting took place. CDF and D0 will resume data taking in early 2001. Later BTeV and the LHC experiments will come online. Here I focus on the "immediate" prospects for observing CP violation in $B$ meson decay, summarising the anticipated precisions from Babar and Belle as well as the Tevatron.

### *3.1 Outlook for* $\sin 2\beta$

The $B$ factory experiments have predicted precisions for several different $B$ decay modes. I summarise their results for decay modes that study $\beta$ in table 3. These are quoted for one year of running at the design luminosity of their respective machines. While the $J/\psi K^0_S$ modes, already studied by OPAL, CDF and ALEPH, will likely yield the highest precision other modes will provide important cross-checks. Final states where the $K^0_S$ decays into $\pi^0\pi^0$ (about 1/3 of the decays), will provide a first test of the $B$ factory experiment's $\pi^0$ reconstruction capabilities. Similarly, the $K^0_L$ decays are more challenging to reconstruct and likely to have lower precision, however they are predicted to have the opposite CP asymmetry from those $K^0_S$ decays. A measurement of $\sin 2\beta$ from these decays that agrees (in magnitude) with that from the $K^0_S$ decays will provide a cross-check of possible charge asymmetries or biases. Finally modes such as $D^{*+}D^{*-}$, while not likely to be statistically competitive with the $J/\psi$ modes but will provide a first arena to study the effect of strong phases obscuring an underlying CP violating angle.

At the Tevatron we anticipate a 20-fold increase in luminosity during the first two years of running. In CDF [a] we expect to increase our $J/\psi K^0_S$ sample

[a] D0 will have similar detector capabilities to CDF during run II. One would expect D0 to make $B$ physics measurements with similar precision during this run.

Table 3. Predictions for measurements of $\sin 2\beta$.

| State | Babar (30 $\mathrm{fb}^{-1}$) | Belle (100 $\mathrm{fb}^{-1}$) | CDF (2 fb−1) |
|---|---|---|---|
| $J/\psi K_S^0(\pi^+\pi^-)$ | 0.12 | 0.10 | 0.08 |
| $J/\psi K_S^0(\pi^0\pi^0)$ | 0.30 | 0.20 | – |
| $J/\psi K_L^0$ | 0.15 | 0.12 | – |
| $D^{*+}D^{*-}$ | 0.44 | – | – |

by improving our silicon vertex detector acceptance by a factor of 1.5. Our projected $\sin 2\beta$ precision is based on a sample of 10,000 $J/\psi K_S^0$ candidates. The control samples used to measure dilution will grow by similar factors. Neglecting the expected improvements in tagging capability we anticipate a precision of $\delta \sin 2\beta \approx 0.08$. By including a time-of-flight detector in CDF-II we should increase our effective tagging capabilities with away-side $K^\pm$ mesons. We also hope to further increase our sample size by including a trigger for $J/\psi \to e^+e^-$ decays. Predictions for similar modes from the $B$ factories can be found in table 3.

### *3.2 Outlook for* $\sin 2\alpha$

Attempts to study CP angles other than $\beta$ will meet significant experimental and theoretical challenges. The next obvious CP eigenstate, $B^0 \to \pi^+\pi^-$, may measure $\sin 2\alpha$. However it suffers from the presence of non-CP violating phases, from penguin decays. Proposals to measure these phases are reviewed in Ref. [6].

Apart from the theoretical complication of interpreting the relative phase of $B^0 \to \pi^+\pi^-$ and $\bar{B}^0 \to \pi^+\pi^-$ there would remain the experimental problem of isolating a clean sample of these decays and measuring their asymmetry. First, and foremost, is the branching fraction $\mathcal{B}(B^0 \to \pi^+\pi^-) = (0.43 \pm 0.18) \times 10^{-5}$ [7]. For the $B$ factories this will make the collection of a significant sample of these decays a fairly long process. The isolation of the $\pi^+\pi^-$ final state is further complicated by the presence of the much larger branching into $B^0 \to K^+\pi^-$, in experiments without particle ID.

Even with the huge $B^0$ production rate at the Tevatron, the absence of particle ID will hinder the separation of $\pi^+\pi^-$ candidates from $K^+\pi^-$ background. The study of $B^0 \to \pi^+\pi^-$ final states at a hadron collider also requires a trigger for $B$ decays into two charged tracks. CDF is developing such a trigger, using information from the silicon vertex detector within 20 $\mu$s of the collision to identify pairs of tracks each having an impact parameter larger than 100 $\mu$m. This trigger will be at least 50% efficient for decays of

$B \to h^+h^-$ and provide the background reduction necessary to make recording these events feasible. Using this trigger we expect $\approx 5000$ $B^0 \to \pi^+\pi^-$ in 2 fb$^{-1}$ (based on the latest branching fractions from CLEO). From this sample, despite a background of 20000 $B^0 \to K^+\pi^-$ decays, we should determine the $\pi^+\pi^-$ charge asymmetry with a precision of 0.13.

Similarly pragmatic studies of the $\pi^+\pi^-$ asymmetry at $B$ factories project uncertainties of 0.15 and 0.26 for one nominal year of running at Belle and Babar, respectively. It remains to be seen whether penguin phases can be sorted out to allow a clean interpretation of this asymmetry in terms of $\sin 2\alpha$.

## 4 Summary

First measurements of the CKM angle, $\beta$, have been made in $B$ meson decay but we are only beginning to study the CP violating effects predicted in the $B$ sector by the CKM matrix. From the measurements to date it is clear that the higher $B$ meson production cross-section in hadron colliders can be a significant advantage in the study of these effects. CDF's 400 event sample provides a more precise measurement of $\sin 2\beta$ than the $\approx 20$ event samples of OPAL and ALEPH, despite the fact that the hadronic backgrounds are larger and the dilutions/efficiencies are smaller. Several measurements of $\sin 2\beta$ with precisions of $\approx$0.1 can be expected before the next meeting in this series. The tools are also in place to collect the data samples necessary for a measurement of $\sin 2\alpha$. However, the theoretical challenges of interpreting observed $\pi^+\pi^-$ asymmetries, in terms of $\alpha$ along with the experimental challenges of separating the $\pi^+\pi^-$ signal from $K^+\pi^-$ (and other) backgrounds will mean that these results will not be available until further into the decade.

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